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^{11}C nuclear data evaluation

Philip R. Page*

Theoretical Division, MS B283, Los Alamos National Laboratory,

Los Alamos, NM 87545, U.S.A.

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Abstract

The final results for the R-matrix analysis of experimental nuclear data on the reactions $^{10}B(p,\alpha_0)\ ^7Be$ and $p\ ^{10}B$ elastic scattering, leading to the ^{11}C intermediate state, are presented. Data for laboratory proton energies from $0.02 - 3$ MeV are entered, yielding an evaluation up to 3 MeV. The data are discussed in detail. The reactions fit with a reasonable $\chi^2/(\text{point})$. The evaluated $^{10}B(p,\alpha_0)\ ^7Be$ cross-section is presented. An evaluated cross-section file in ENDF format is prepared for the reactions $^{10}B(p,\alpha_0)\ ^7Be$ and $p\ ^{10}B$ elastic scattering. Maxwellian averaged cross-sections in NDI format are prepared for the reaction $^{10}B(p,\alpha_0)\ ^7Be$.

1 General features of the fit

It is determined that reactions involving $n\ ^{10}C$ are not of central significance to the weapons program, and hence reactions involving $p\ ^{10}B$ and $\alpha\ ^7Be$ are evaluated for the first time. The current analysis is the first evaluation ever performed for the ^{11}C system, except for an evaluation of the astrophysical S-factor for $^{10}B(p,\alpha_0)\ ^7Be$ [1]. An R-matrix fit (using the EDA code [2]) of the elastic reaction $^{10}B(p,p_0)\ ^{10}B$ (up to D-wave) and of the exothermic reaction $^{10}B(p,\alpha_0)$ (up to F-wave) is performed. The data range from $0.02 - 3$ MeV using data sets from ten experimental references with 1845 data points. The $^{10}B(p,\alpha_0)\ ^7Be$ data (248 points) range from $0.02-3$ MeV, while $^{10}B(p,p_0)\ ^{10}B$ (1597 points) range from $0.5-3$ MeV. For the latter reaction no cross-section data below 0.5 MeV were found. A detailed discussion of the data included can be found in the next section.

* *E-mail: prp@lanl.gov*

Reaction	χ^2/p	Reaction	χ^2/p
$^{10}B(p,\alpha_0)\ ^7Be$	6.1	$^{10}B(p,p_0)\ ^{10}B$	0.97

Table 1: χ^2 / (data point) for the various reactions.

The current fit has 25 free parameters for the two channels $p\ ^{10}B$ and $\alpha\ ^7Be$. The R-matrix radius parameter for the former channel is 4.5 fm, and for the latter 5 fm. The fit incorporates three well-known resonances ($J^\pi = \frac{5}{2}^+, \frac{7}{2}^+$ and $\frac{9}{2}^+$ at respectively $E_p =$ 0.01, 1.53 and 2.19 MeV), and prefers several broader resonances and backgrounds. These three resonances are needed in all versions of the fit. The angular distribution of the cross-section is given by the J^π structure of the resonances and backgrounds, which is determined by the Chiari 2001 data from $0.5-3$ MeV [3], and by the known $\frac{5}{2}^+$ resonance at $E_p = 0.01$ MeV. The χ^2/(point) is listed for each reaction in Table 1. The elastic scattering data of Chiari 2001 [3] fit remarkably well, after the statistical and systematic errors are inflated, as discussed in the next section. The overall χ^2 per degree of freedom is 2.2.

There are 4 different reactions for which cross-sections can be obtained via this analysis. These are $p\ ^{10}B,\ \alpha\ ^7Be \to p\ ^{10}B,\ \alpha\ ^7Be$. In addition to unitarity, constraints between reactions are also provided by time-reversal symmetry (i.e. when the initial and final particles are interchanged). For example, no data were entered for $^7Be(\alpha,p_0)\ ^{10}B$ and $^7Be(\alpha,\alpha_0)\ ^7Be$, because there is no known experimental data for these reactions. The former reaction is constrained by time-reversal symmetry to $^{10}B(p,\alpha_0)\ ^7Be$ for which data was entered.

The $^{10}B(p,\alpha_1)^7Be^*$ and $^{10}B(p,{}^3He)$ reactions open in the energy range studied. The former reaction is negligible up to about 2.4 MeV [4, 5] and the latter appears to be negligible over the energy range of interest, although data is only known above 3.8 MeV [6]. The possibility of these reactions is hence neglected. There is no known experimental data for the reaction $^7Be(\alpha,\ ^3He)$.

2 Data included

2.1 $^{10}B(p,\alpha_0)\ ^7Be$

Angulo 1993 [4]: The cross-section was measured in the energy range $17 < E_p < 134$ keV. The cross-section as converted from the S-factor in Table 2 (p. 239 [4]) is entered. The data points corresponding to the two lowest energies are corrected for effects of electron screening according to the size of the effects shown in Fig. 10 (p. 240 [4]). Ground and excited ^7Be product states are *not* separated, although the contribution from excited ^7Be

is expected to be negligible [5].

Relative error: Errors in Table 1: “Errors quoted arise from uncertainties in number of counts, effective energy, and target deterioration.” (p. 239 [4]) The data point scatter in Fig. 10 makes it clear that the errors must have been underestimated. All errors are hence multiplied by a factor of 1.5.

Normalization error: The error is 6%: “All values have a common error of 6% due to uncertainties in N_p, Ω_{lab} and ϵ_{eff}.” (p. 239 [4])

Knape 1992 [7]: The cross-section was measured in the energy range $37 < E_p < 120$ keV. Ground and excited ^7Be product states are clearly separated.

Relative error: Read from Fig. 4: “The error bars include the proton energy uncertainty $(1 - 2$ keV).” (p. 178 [7])

Normalization error: Since there is no normalization error discussion it is set to infinity.

Szabo 1972 [8]: The cross-section was measured in the energy range $100 < E_p < 180$ keV by the activation method (Method I) and in the $60 < E_p < 180$ keV range by detecting α-particles directly (Method II). In Method I cross-sections to ground ^7Be product states are clearly separated. This is not the case in Method II. Here there are additional contamination from additional sources: “For energies $E_p \geq 160$ keV the cross-section data obtained by the direct α-measurements are higher than the corresponding values measured with the activation method and are outside the error limits. The difference is due to the reaction $^{11}B(p, \alpha)^8Be$ which has a resonance at $E_p = 163$ keV.” (p. 531 [8]) The contribution from excited ^7Be is expected to be negligible [5]. The points with $E_p \geq 160$ keV obtained with Method II are accordingly excluded from the fit. Integrated data in the range $60 - 180$ keV Table 1 (p. 530 [8]) were entered.

Relative error: Since there is no error discussion the errors in Table 1 (p. 530 [8]) are assumed to be relative errors only.

Normalization error: Since there is no error discussion the error is set to infinity.

Youn 1991 [9]: The cross-section was measured in the energy range $120 < E_p < 480$ keV. The cross-section from Table 1 (p. 329 [9]) is entered. Ground and excited ^7Be product states are clearly separated.

Relative error: Differential cross-section: “The errors in Fig. 2a,b were determined by statistical errors, errors due to target thickness, beam energy uncertainties, and solid errors ...” (p. 324 [9]) The cross-section errors are determined from the differential cross-section errors, and are treated the same: “The total cross section ... were derived from the differential cross sections of fig. 2a”.

Normalization error: The relative error already includes some of the elements which go into the normalization error, but not all (e.g. the beam current is not included). The normalization is hence set to infinity.

Brown 1951 [10]: This data were measured in the energy range $0.615 < E_p < 1.114$ MeV and $1.208 < E_p < 1.585$ MeV with different target arrangements and hence separate normalizations: "The cross-section ... was measured for proton energies from 615 keV to 1114 keV and from 1208 keV to 1585 keV. It was necessary to use different target arrangements in the two energy ranges to avoid scattered protons." (p. 166 [10]) The differential cross-section $^{10}B(p,\alpha_0)$ data of Fig. 9 (p. 169 [10]) are entered. The cross-section is in the C.M. system "Cross-sections ... in the center of mass system" (p. 169 [10], caption of Fig. 9), the energy is in the laboratory system "laboratory proton energy" (p. 169 [10], caption of Fig. 9), and the angle 137.8^o in the laboratory system: "All the angles listed above are in the laboratory system of coordinates and are measured relative to the direction of the incident proton beam" (p. 166 [10]). The laboratory angle 137.8^o is converted to the C.M. system, as required for EDA input. All cross-sections in Fig. 9 are converted from barns/(4π ster) to mb/ster units. Ground and excited ^7Be product states are clearly separated.

Relative error: Errors are given in Fig. 9 (p. 169 [10]). These error bars are clearly too small, as the different neighboring points differ by much more than the size of their errors from each other. To correct for this effect, the errors on both data sets are inflated by a factor of 4.

Normalization error: A 20% error is assigned separately to the lower and higher energy data sets: "There is, in addition to statistics, an uncertainty of 20% in the scale of the ordinate, due principally to poor knowledge of the boron stopping cross section ..., to statistical uncertainty in the determination of N, to uncertainty in the ratio of the integral ..., to uncertainty in the background corrections, and to uncertainty in the factor f." (p. 168 [10]) The data at higher energy may be too low: "BSFL mentions that their data may be low at higher bombarding energies" (p. 305 [11]) Setting the normalizations of the low and high energy data to be different is problematic because of the large normalization uncertainties. In the absence of other data that spans the entire energy region, the two normalizations are set equal in the fit.

Cronin 1956 [11]: Differential cross-sections at 1.2 and 1.5 MeV are entered from Tables 3 and 4 (p. 304-305 [11]). The angles ($\theta = 90^o$) and cross-sections are measured in the laboratory frame: "The absolute cross section was measured at 1.5 MeV bombarding energy and 90^o in the laboratory frame." (p. 303 [11]). "The BSFL cross-section are corrected to $90^o_{lab}\ldots$" (p. 305 [11]). These quantities are converted from the laboratory to the C.M. frame. The energy is uncertain to 3% (Table 3, p. 304 [11]), which is implemented by allowing the energies to shift in EDA. However, the infinite normalization error (discussed below) do not allow the fit to exploit the energy uncertainty. Ground and excited ^7Be product states are clearly separated.

Relative error: The errors in Tables 3 and 4 (p. 304-305 [11]) are used.

Normalization error: Because the errors in Tables 3 and 4 include many more errors than just the statistical error, although not all errors (e.g. uncertainty in beam current), the normalization error is largely already included in the relative error is discussed above. The normalization is set to infinity.

Overley 1962 [12]: Differential cross-sections from $1.5 - 2.6$ MeV at a laboratory angle of 90^o were measured and displayed in Fig. 7, and entered from EXFOR, where it is incorrectly stated that the energies are in the C.M. frame. The cross-sections in Fig. 7 are in the C.M. frame but the laboratory angle of 90^o was converted to the C.M. frame. Ground and excited ^7Be product states are clearly separated.

Relative error: "Our estimate of the non-systematic uncertainty is $\pm 2\%$." (p. 320 [12]) A close inspection of the points show that the scatter is much larger. Based on this scatter the relative error is taken to be 6%.

Normalization error: Taken to be 10%: "The uncertainty in the cross section is estimated to be $\pm 10\%$. The uncertainty arises largely from the quantity K and is systematic." (p. 320 [12]) "The quantity K, which depends on the spectrometer resolution and solid angle, the number of protons incident on the target, and the detection efficiency ..." (p. 317 [12]).

Jenkin 1964 [5]: The cross-section was measured in the energy range $1.8 < E_p < 10.8$ MeV. Data points in the range $2.8 < E_p < 7.0$ MeV are entered, but only those up to 3.0 MeV are fitted. The cross-section from Fig. 5 (p. 521 [5]) is entered. The differential cross-section at 90^o laboratory angle (Fig. 2, p. 517 [5]) is also entered, and the laboratory cross-sections and angles (caption, fig. 2) are converted to the C.M. frame. An earlier publication of the 90^o differential data [6] does not agree exactly with the data in the newer publication, e.g. in number of points and normalization. Ground and excited ^7Be product states are clearly separated.

Relative error: Integrated data (Fig. 5): "The errors shown are the residual errors as defined by Rose, which contain the statistical errors." (p. 520) Differential data: No error bars are indicated in Fig. 2, and an estimate of 10% based on the scatter of the points is used.

Normalization error: Since there is no error discussion the error is set to infinity.

2.2 $p\ ^{10}B$ elastic

Chiari 2001 [3]: Differential cross-sections from 0.5 to 3.3 MeV are entered from EXFOR. The data comes in increments of 0.025 MeV and constitutes a huge data set with 1597 points. Data up to 3.0 MeV are fitted. Part of this data can be found in Fig. 5 and Table 2. The angles and cross-sections are in the laboratory frame: "... the cross-section ... (laboratory frame of reference)" (caption, Table 2) They are hence converted to the C.M. frame. Ground and excited ^{10}B product states are clearly separated: "The elastic peaks from different elements were in general well separated; also no interferences were present

Reaction	Data Ref.	E (MeV)	Data Ref.	E (MeV)
$^{10}B(p,\alpha_0)\ ^7Be$	Angulo 1993 [4]	$0.02 - 0.15$	Knape 1992 [7]	$0.04 - 0.12$
	Szabo 1972 [8]	$0.06 - 0.18$	Youn 1991 [9]	$0.21 - 0.46$
	Brown 1951 [10]	$0.61 - 1.5$	Cronin 1956 [11]	$1.2 - 1.5$
	Overley 1962 [12]	$1.5 - 2.6$	Jenkin 1964 [5]	$1.8 - 3.0$
$^{10}B(p,p_0)\ ^{10}B$	Chiari 2001 [3]	$0.5 - 3.0$		

Table 2: Data in the ^{11}C analysis. The laboratory energy of the projectile is E.

between the elastic scattering peaks on ^{10}B and ^{11}B and peaks due to nuclear reactions and an-elastic [*sic*] scatterings." (p. 313 [3])

Relative error: The statistical error ($< 2\%$) is added to the error in the solid angle (0.5%, below) to give a relative error of 2.5%: "… the $< \pm 2\%$ statistical error for ^{10}B." (p. 317 [3]) The statistical errors indicated in Fig. 5 are estimated to be 5%. This discrepancy between the text and Fig. 5 is resolved by adopting the most conservative value, 5%.

Normalization error: A conservative estimate is that this is 2.5% by just adding the individual contributions: "… the contributions to the error in the cross-section value are: $\pm 0.5\%$ (solid angle), $\pm 1.5\%$ (target thickness), $\pm 1.0\%$ (integrated current)." (p. 317 [3]) The R-matrix fit shows that a much larger normalization uncertainty is needed. A value of 7.5% is adopted. There should be a separate normalization for each energy, because the measurements were taken by running at a specific energy, and then taking data at all angles simultaneously: "During the different runs, proton beam currents were … Each run was allowed to continue until obtaining at least 10^4 counts in the elastic scattering peak on ^{11}B at all angles; this implied run times of about $15 - 20$ min."(p. 311-312 [3])

In summary, integrated cross section data come from Angulo 1993 [4], Knape 1992 [7], Szabo 1972 [8], Youn 1991 [9] and Jenkin 1964 [5]. Excitation function data at a specific angle come from Brown 1951 [10], Cronin 1956 [11] and Jenkin 1964 [5]. Differential cross section data for various angles come from Chiari 2001 [3].

Table 2 contains a complete list of the data in the ^{11}C analysis.

3 Cross-sections

The cross-section for the $^{10}B(p,\alpha_0)\ ^7Be$ reaction in the energy range $0.02 - 3$ MeV is shown in Fig. 1. The experimental (integrated) cross-section data that are part of the R-matrix fit are indicated. This represents all the integrated data known in the energy region of interest, except for two data sets. These are Bach 1955 [13], which strongly disagrees with modern measurements in shape, and Burcham 1950 [14], which, possibly

Figure 1: The $^{10}B(p,\alpha_0)\ ^7Be$ cross-section. Experimental data are from Angulo 1993 [4], Knape 1992 [7], Szabo 1972 [8], Youn 1991 [9] and Jenkin 1964 [5]. The numbers of the sets for the Szabo data correspond to the numbers of the methods discussed in the text.

Figure 2: The $^{10}B(p,\alpha_0)\ ^7Be$ differential cross-section at 90^o laboratory angle. Experimental data are from Overley 1962 [12] and Jenkin 1964 [5].

incorrectly, assumes isotropic distributions in the derivation of the integrated cross-section. The $^{10}B(p,\alpha_0)\ ^7Be$ reaction clearly shows several resonance peaks above 0.8 MeV for which some of the corresponding resonances are mentioned in the first section. The large renormalizations needed for the modern Youn 1991 [9] and Angulo 1993 [4] data are not *a priori* a concern if it is noted that these reactions disagree by large factors: "... the absolute data from Ref. [9] has been normalized by a factor of 1.83 to that of the present work [Ref. [4]] at overlapping energies." (p. 240 [4]). It is comforting that the Chiari 2001 data [3], which is available above 0.5 MeV, determine the normalizations of the Youn 1991 and Angulo 1993 data, while itself fitting with normalizations within 4% of the experimental value. The normalization of the low-energy $^{10}B(p,\alpha_0)$ data is hence strongly constrained by the $^{10}B(p,p_0)\ ^{10}B$ data. The same is true about the other $^{10}B(p,\alpha_0)$ data. The exact normalizations of this data above 1.5 MeV have changed considerably at various stages of the analysis.

The differential cross-section for $^{10}B(p,\alpha_0)\ ^7Be$ in the $1.5-3$ MeV energy region is shown in Fig. 2. The well-known $\frac{9}{2}^+$ resonance is clearly visible.

An evaluated cross-section file in ENDF format is prepared for the reactions $^{10}B(p,\alpha_0)\ ^7Be$ and $^{10}B\ p$ elastic scattering in the energy range $0.01-3$ MeV.

Maxwellian averaged cross-sections are prepared for the reaction $^{10}B(p,\alpha_0)\ ^7Be$ in the NDI format. The low-energy behavior of the cross-section is *not* given by the usual Gamov form for a charged particle projectile, because of the resonance at $E_p = 10$ keV. Because the lowest data point is at 20 keV (Angulo 1993 [4]), this means that the Maxwellian averaged cross-sections may not be very accurate below a temperature of about 10 keV, although the inclusion of the correct physics by EDA should ensure reasonable predictions.

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